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U. S. NAVAL AIR MATERIAL CENTER
PHILADELPHIA 12, PA.

AERONAUTICAL ENGINE LABORATORY

NAMC-AEL-1674 8 FEB 1961

HIGH STRENGTH REFRACTORY ALLOYS

BY
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PHASE A REPORT ON
BUWEPS P. A. NAM-RAPP33001

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mlm

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I. INTRODUCTION

In order to improve the mission capability and reliability of aircraft and missiles, materials subjected to the high temperatures which exist in gas turbine engines, nuclear powerplants, and re-entry vehicles, and other systems must be improved. To meet this requirement the Bureau of Naval Weapons is supporting a Refractory Metals Development Program at the Naval Research Laboratory (NRL problem No. M01-12). The project is concerned with improving the oxidation resistance of columbium, tantalum, and tungsten by alloying or coating or both. The AEL was authorised by Bureau of Naval Weapons letter RAPP-33/1:JJL of 24 March 1960 to test materials developed by NRL at conditions (within laboratory capability) which are representative of the environment to which the metals might be exposed. The cognisant NRL and BUWEPS personnel have been kept abreast of the test results through monthly newsletters and personal contact.

II. SUMMARY OF RESULTS

a. The zinc coated columbium material failed when exposed to the exhaust gases resulting from the combustion of the following fuels with air at the temperatures and velocities indicated:

(1) Hydrogen - 1800°F, 60 feet per second

(2) Propane - 2200°F, 760 feet per second

(3) JP-4 - 2300°F, 1400 feet per second

b. The zinc coated columbium plus 2% zirconium material failed when exposed to the exhaust gases resulting from the combustion of the following fuels with air at the temperatures and velocities indicated:

(1) Hydrogen - 1800°F, 60 feet per second

(2) Propane - 2000°F, 500 feet per second

(3) JP-4 - 2100°F, 2400 feet per second

c. A columbium plus 2% zirconium rod with a zinc coating was exposed to a simulated reducing environment at a test temperature of 1800°F without any detrimental effect to the coating.

III. CONCLUSIONS

The zinc coated columbium and columbium plus 2% zirconium materials do not offer any significant gains with respect to permitting higher turbine inlet temperatures for air breathing gas turbine engines. Current maximum localized turbine inlet hot spot temperatures are in the range of the maximum satisfactory operating temperatures of the two materials tested.

IV. RECOMMENDATION

It is recommended that the zinc coated columbium and columbium plus 2% zirconium materials not be considered for use as gas turbine engine combustion and turbine component materials.

V. DESCRIPTION OF MATERIAL

a. Two materials were supplied to AEL for testing over a range of temperatures and velocities with various fuels. The first was a pure columbium rod with a zinc coating; the second was a columbium rod containing a 2% addition of zirconium with a zinc coating.

b. The materials to be tested were cylindrical in shape with a diameter of 0.1 inch and a length of approximately 2 7/8 inches. Most of the rods supplied had surface areas on which a scale was present resulting from the technique used in their fabrication. Also, the surfaces of the rods were irregular.

c. The high temperature gases were supplied by the combustion of the following fuels:

(1) Hydrogen (technical grade) having a minimum of 99% by volume of hydrogen as specified in Federal Specification BB-H-886.

(2) Propane containing a minimum of 95% by volume of propane as specified in the Natural Gasoline Association of America Publication 2140.

(3) Jet fuel grade JP-4 conforming to Specification MIL-J-5624.

d. Technical grade benzene was used in tests numbered 5 and 6 which conformed to Federal Specification VV-B-231C.

VI. METHOD OF TEST

a. The high temperature combustion exhaust gases to which the test pieces were subjected were supplied by a burner. The test pieces were held in a test section immediately downstream of the burner. A schematic drawing of the test facility is shown on plate 1.

b. Plate 1 shows the test section mounted in the test facility. Metered air enters the burner through the inlet air duct. In the burner, fuel is injected into the air and burned thus providing the high temperature exhaust gases required to test the materials mounted in the test section. The view port, which was inclined 60° from the direction of flow on the upstream side of the test section, provides visual observation of the rods during the test. The state (pressure, temperature, and velocity) of the exhaust gases is determined by instrumentation immediately downstream of the test section. A rake of three thermocouples is used for temperature measurement and the pressure at the test section is measured by a rake of three total pressure probes. The test temperatures reported throughout the report refer to the maximum gas stream temperature as measured by the rake of three total temperature thermocouples. The relationship between the surface temperature of the test materials and the gas stream temperature was determined with the aid of thermocouples welded on the surface of several stainless steel test rods. The burner was operated at several gas stream temperatures with the surface temperature of the instrumented rods recorded for each gas stream temperature. The maximum surface temperature and the maximum gas stream temperature are nearly identical as indicated by the data shown on plate 2. The agreement in surface and gas stream temperatures is due largely to the method by which the test rods are held in the test section which minimizes heat transfer losses from the rods. The velocity at the test section was derived from the other measured quantities. The sections of the duct work downstream of the burner are wrapped with asbestos to reduce heat transfer losses by convection and radiation of the walls to their surroundings.

c. The test rods were mounted normal to the direction of flow of the burner exhaust gases and are shown mounted in the test section in plate 3. Based on NRL's warning that a compatibility problem might exist due to contact between the test material and the materials used in the test section, a test section was designed that would minimize this problem. Plate 4, which is a view of the disassembled test section, shows the means by which this problem was circumvented. The three large porcelain beads are used to support and insulate the test rods while the slender porcelain strips are used to locate the rods centrally. The string asbestos is used to allow for lengthwise expansion of the test pieces at elevated temperatures. The setscrews hold all of the above in place during the test. Plate 3 shows the test section assembled. All of the items shown on plate 4 have been used in this assembly.

d. The weight flow of the air and gaseous fuels used was determined by means of orifice plates. The weight flow of the liquid fuel was determined by the use of a calibrated rotameter.

e. The exhaust products of the combustion process were ducted to the plant exhaust system.

f. All of the tests were of five hours' duration except test number 7 which was terminated after two hours and forty minutes due to facility problems.

g. At twenty-minute intervals, the rods were inspected visually and readings of all the instrumented variables were taken to insure that the proper test conditions were being maintained.

h. In order to determine the stability at high temperatures of the zinc coating, carbon which has a high affinity for oxygen was placed on the surface of a rod. The carbon deposit was obtained by rotating the test rod in the reducing flame of a bunsen burner burning natural gas which had bubbled through a container of benzene. In test number 5 one alloy rod coated as described above and one alloy rod without a carbon deposit (control rod) were tested using propane (C_3H_8) as the fuel for the burner.

i. In order to check the stability of the coating when in a continuously carbon enriched environment, the burner fuel, propane, was permitted to bubble through a cylinder containing benzene prior to injection into the burner. This procedure was used in test number 6.

j. The composition of the exhaust gases was determined with a Scholander micro gas analyzer technique which uses an absorption principle for its measurements.

VII. ANALYSIS OF RESULTS AND DISCUSSION

a. The success or failure of the materials tested at AEL was determined by visual inspection during and after the test. It was possible by visual inspection to determine changes in the surface condition of the materials. These changes fell into the following categories:

(1) Surface corrosion

(a) Surface changes that either appeared as a deposit or as a change in color were reported as surface corrosion.

(2) Rupture of coating

(a) This change was evidenced by the absence of a portion of the coating or a bulging of the coating. This could possibly result from a difference in the expansion rate between the coating and the base material.

(3) Needle-like growths

(a) These growths originated at the surface of the test materials and proceeded to grow outward from the surface. In most cases the apparent ratio of the length to diameter of these growths was greater than 4:1. These growths are possibly the same as the single crystals of $\alpha - Nb_2O_5$ ($\alpha - Cb_2O_5$) found to grow on the oxide surface of columbium above 1472°F which was described in Technical (Scientific) Note No. 2 of April 1960, "High Temperature Oxidation of Niobium" by Per Kofstad, Hallstein Kjøllesdal, Joar Markali, and Nico Norman at the Central Institute for Industrial Research in Oslo-Blindern-Norway.

b. Table I lists the test number and the materials used in that test. The table also indicates the object of each test, the actual conditions of the test, and pertinent remarks as to the results of the test.

TABLE I

SUMMARY OF TESTS

Test No.	Fuel	Max. Temp. °F	Max. Velocity Ft/Sec	Press. (In. of Hg)	Materials Tested: Zn Coated Cb	Materials Tested: Zn Coated Cb-2% Zr	Aim	Visual Observations And Comments
1	H_2	1600& 1800	20	32	1	1	Effect of Velocity and Temperature	Check of Equipment. These conditions were maintained for one hour without either rod showing any adverse effects.
	H_2	1600	38	32	1	1	Effect of Velocity and Temperature	These conditions were maintained for one hour without either rod showing any adverse effects.
	H_2	1800	40	32	1	1	Effect of Velocity and Temperature	The temperature peaked to 1900°F and the Zn coated Cb rod developed a white coating and blistered. The Zn coated Cb-2% Zr rod had a slight white coating.
2	H_2	1600	40 & 60	32	1	1	Effect of Velocity and Temperature	The rods from test 1 were still being used. Both rods appear to have a white coating.
	H_2	1800	40 & 60	32	1	1	Effect of Velocity and Temperature	Temperature increased from 1600 to 1800°F. Both rods appear to have a white coating.

TABLE I (CONT)

SUMMARY OF TESTS

Test No.	Fuel	Max. Temp. °F	Max. Velocity Ft/Sec	Press. (In. of Hg)	Materials Tested: Zn Coated Cb	Materials Tested: Zn Coated Cb-2% Zr	Aim	Visual Observations And Comments
3	H_2	1800	60	32	1	1	Endurance Test at Temperature	The rods from test No. 1 were used again. Both rods have a white coating. The Zn coating on both rods appears to have ruptured exposing the base metal.
4	C_3H_8	1800	60	32	1	1	Effect of Hydrocarbon Fuel	Both rods appeared satisfactory throughout test.
5	C_3H_8	1800	60	32	0	2	Stability of Coating in a Simulated Reducing Environment (Carbon as Reducing Agent)	Two Zn coated Cb-2% Zr rods were tested. One rod had a carbon deposit placed on it prior to testing; the other rod was used as a control. Both rods failed after a piece of asbestos had fallen on them.
6	C_3H_8	1800	60	32	0	1	Stability of coating in a Simulated Reducing Environment (Carbon as a Reducing Agent)	One Zn coated Cb-2% Zr rod was tested in a continuously benzene enriched C_3H_8 exhaust. The rod did not appear adversely affected.

TABLE I (CONT)

SUMMARY OF TESTS

Test No.	Fuel	Max. Temp. °F	Velocity Ft/Sec	Press. (In. of Hg)	Materials Tested: Zn Coated Cb	Materials Tested: Zn Coated Cb-2% Zr	Aim	Visual Observations And Comments
7	C_3H_8	$\leq$1950	Varying	32	1	1	Effect of Varying Temperature	The coating on the Cb-2% Zr rod failed adjacent to the holder (asbestos had possibly caused the failure). The Zn coated Cb rod had a slight amount of surface corrosion.
8	H_2	1800	60	32	1	1	Endurance Test at Temperature	Check of test No. 3. The Zn coated Cb-2% Zr rod developed needle like growths. The Zn coated Cb rod had a slight break in the coating.
9	C_3H_8	1800	500	32	1	1	Effect of Velocity and Temperature	Both rods had some surface corrosion. The Zn coated Cb rod appeared to have more surface corrosion than the Zn coated Cb-2%Zr rod.
10	C_3H_8	2000	500	32	1	1	Effect of Velocity and Temperature	Both rods had some surface corrosion. The coating on Cb-2% Zr rod had ruptured.

TABLE I (CONT)

SUMMARY OF TESTS

Test No.	Fuel	Max. Temp. °F	Velocity Ft/Sec	Press. (In. of Hg)	Materials Tested: Zn Coated Cb	Materials Tested: Zn Coated Cb-2% Zr	Aim	Visual Observations And Comments
11	C_3H_8	2200	760	32	1	1	Effect of Velocity and Temperature	Both rods had some surface corrosion. The temperature was increased for 5 min to 2200°F and both rods developed needle like growths.
12	JP-4	1875 1610	1330	34	1 0	0 1	Effect of Velocity and Temperature	The Zn coated Cb-2% Zr rod was unaffected. The Zn coated Cb rod had surface corrosion over most of its length with one area that appeared to have blistered and "healed."
13	JP-4	2310 2050	1400	34	1 0	0 1	Effect of Velocity and Temperature	The Zn coated Cb which was at a max temperature of 2310°F failed. The Zn coated Cb-2% Zr had some surface corrosion.
14	JP-4	2000 1625	1400	33	1 0	0 1	Effect of Velocity and Temperature	The Zn coated Cb rod had some surface corrosion whereas the Zn coated Cb-2% Zr rod was unaffected.

TABLE I (CONT)

SUMMARY OF TESTS

Test No.	Fuel	Max. Temp. °F	Velocity Ft/Sec	Press. (In. of Hg)	Zn Coated Cb	Zn Coated Cb-2% Zr	Aim	Visual Observations And Comments
15	JP-4	2000 1625	1400	37	0 1	1 0	Effect of Velocity and Temperature	Both rods had some surface corrosion. The coating on one area of the Zn coated Cb rod appeared to have blistered and "healed."
16	JP-4	2110 1825	2400	40	1 0	0 1	Effect of Velocity and Temperature	The Zn coated Cb rod which was at a maximum temperature of 2110°F fell out of the test section and failed. The Zn coated Cb-2% Zr rod had some surface corrosion.
17	JP-4	2110 1825	2400	40	0 1	1 0	Effect of Velocity and Temperature	The Zn coating on the Cb-2% Zr rod which had a maximum temperature of 2110°F failed. The Zn coated Cb rod had some surface corrosion.
18	JP-4	2110 1825	2400	40	1 0	0 1	Effect of Velocity and Temperature	Check of test No. 16. Both rods have some surface corrosion and are bent due to aerodynamic loading.

c. In tests numbered 1, 2, 3, and 8, both the zinc coated columbium and the zinc coated columbium plus 2% zirconium were exposed to exhaust gases from the combustion of hydrogen and air. Both materials failed when exposed to an exhaust gas temperature of 1800°F. As can be seen on plates 5 and 6, the coating on the columbium rod had ruptured slightly, whereas several needle-like growths had developed on the surface of the columbium plus 2% zirconium rod.

d. The aim of tests numbered 5 and 6 was to determine the stability at high temperatures in a simulated reducing environment of the zinc coating used on the columbium materials. This was accomplished in test number 5 by exposing two zinc coated columbium plus 2% zirconium rods to a temperature of 1800°F after coating one of the rods with carbon as described in paragraph 8 of Method of Test. The 1800°F exhaust gases resulted from the combustion of propane with air. At the beginning of the test a portion of the asbestos gasket used as a seal between the flanges of the ducting broke off and impinged on the rods. Approximately twenty minutes had elapsed before this condition was observed and the test was interrupted to permit the removal of the asbestos. After resuming the test, the coating on the rod with the carbon deposit, which was the rod that most of the asbestos had impinged on, began to bulge and continued bulging throughout the remainder of the test. The bulged surface of the rod eventually ruptured, exposing the columbium plus 2% zirconium material to the high temperature environment. At the completion of the test it was observed that the central portion of this rod was void in the region of the rupture, leaving only the bulged surface. This portion of the rod shattered before a photograph could be taken. Surface corrosion was present on the remainder of the rod which is shown on plate 7. The columbium plus 2% zirconiu rod without a carbon deposit (control rod) did not bulge but corrosion of the surface had taken place. A considerable portion of the surface of this rod separated from the inner layers. This condition is shown on plate 8. The section of the surface which fell off coincided with that portion of the rod which had been in contact with the asbestos. The asbestos material is wire reinforced and contains a rubber bonding agent in conformance with specification number Fed HH-P-31 which calls for at least 90% Chrysotile asbestos and 10% Cotton as a maximum. The wire reinforcing is a brass wire of 0.007±0.001 in. diameter. The composition of Chrysotile asbestos obtained from "The Encyclopedia of Chemistry" by Clark and Hawley of 1957 is as follows:

Constituent	Weight Percent
SiO_2	37-44
MgO	39-44
FeO	0.0-6.0
Fe_2O_3	0.1-5.0
Al_2O_3	0.2-1.5
H_2O	12.0-15.0
CaO	Tr-5.0

N.R.L. was informed of the details of this test and the materials were given to them so that any metallurgical or chemical tests that were desired could be performed. Whether the failure of these rods can be attributed to an incompatibility between the zinc coating and asbestos has not been determined.

e. During test number 6 one zinc coated columbium plus 2% zirconium rod was exposed to an 1800°F exhaust gas environment resulting from the combustion of propane which had been bubbled through a cylinder containing benzene. This technique exposed the rod continually to high temperature carbon enriched exhaust gases. The zinc coated columbium plus 2% zirconium rod was not adversely affected by the environment noted above.

f. In tests numbered 4, 7, 9, 10, and 11 zinc coated columbium and zinc coated columbium plus 2% zirconium rods were exposed to exhaust gases produced by the combustion of propane with air. The results of these tests are pictorially summarized on plate 9 for the zinc coated columbium material and on plate 10 for the zinc coated columbium plus 2% zirconium material. These tests indicate that the zinc coated columbium material must be used at temperatures below 2200°F, whereas the zinc coated columbium plus 2% zirconium material must be used at temperatures below 2000°F when placed in an exhaust gas environment resulting from the combustion of propane with air.

g. In tests numbered 12 through 18 the test pieces were exposed to exhaust gases resulting from the combustion of a liquid fuel (JP-4) with air. Due to the temperature distribution at the exit of the liquid fuel burner the two test pieces were at different temperatures. The temperatures indicated in table I and throughout the body of the report refer to the maximum gas stream temperature impinging on each rod for these tests.

h. In tests numbered 12, 13, 14, 15, 17, and 18 zinc coated columbium and zinc coated columbium plus 2% zirconium rods were exposed to exhaust gases produced by the combustion of JP-4 with air. The results of these tests are pictorially summarized on plates 11 and 12 for the zinc coated columbium material and on plates 13 and 14 for the zinc coated columbium plus 2% zirconium material. This series of tests indicates that the zinc coated columbium material must be used at temperatures below 2300°F, whereas the zinc coated columbium plus 2% zirconium material must be used at temperatures below 2100°F when placed in an exhaust gas environment resulting from the combustion of JP-4 with air.

i. In test number 18 both rods had suffered a permanent deformation due to the aerodynamic loading at the temperature of the test. This deformation is not considered significant since it could be reduced to any acceptable amount by increasing the cross-sectional area of the rods.

j. Samples of the exhaust gases were taken in tests numbered 8 and 9 and analyzed with a Scholander micro gas analyzer to determine the weight percentage of carbon dioxide (CO_2) and oxygen (O_2). In test number 8, since hydrogen was used as the fuel in the burner, the determination of the carbon dioxide content was omitted. For test number 8 it was determined that oxygen comprized 16.3% by weight of the exhaust gases. In test number 9 it was determined that the exhaust gases contained 14.7% by weight of oxygen and 6.7% by weight of carbon dioxide.

k. Table II summarizes the test results indicating the apparent success or failure of the materials at various temperatures and velocities. The test was considered a failure if the coating of the material ruptured, blistered, or developed needle-like growths.

TABLE II

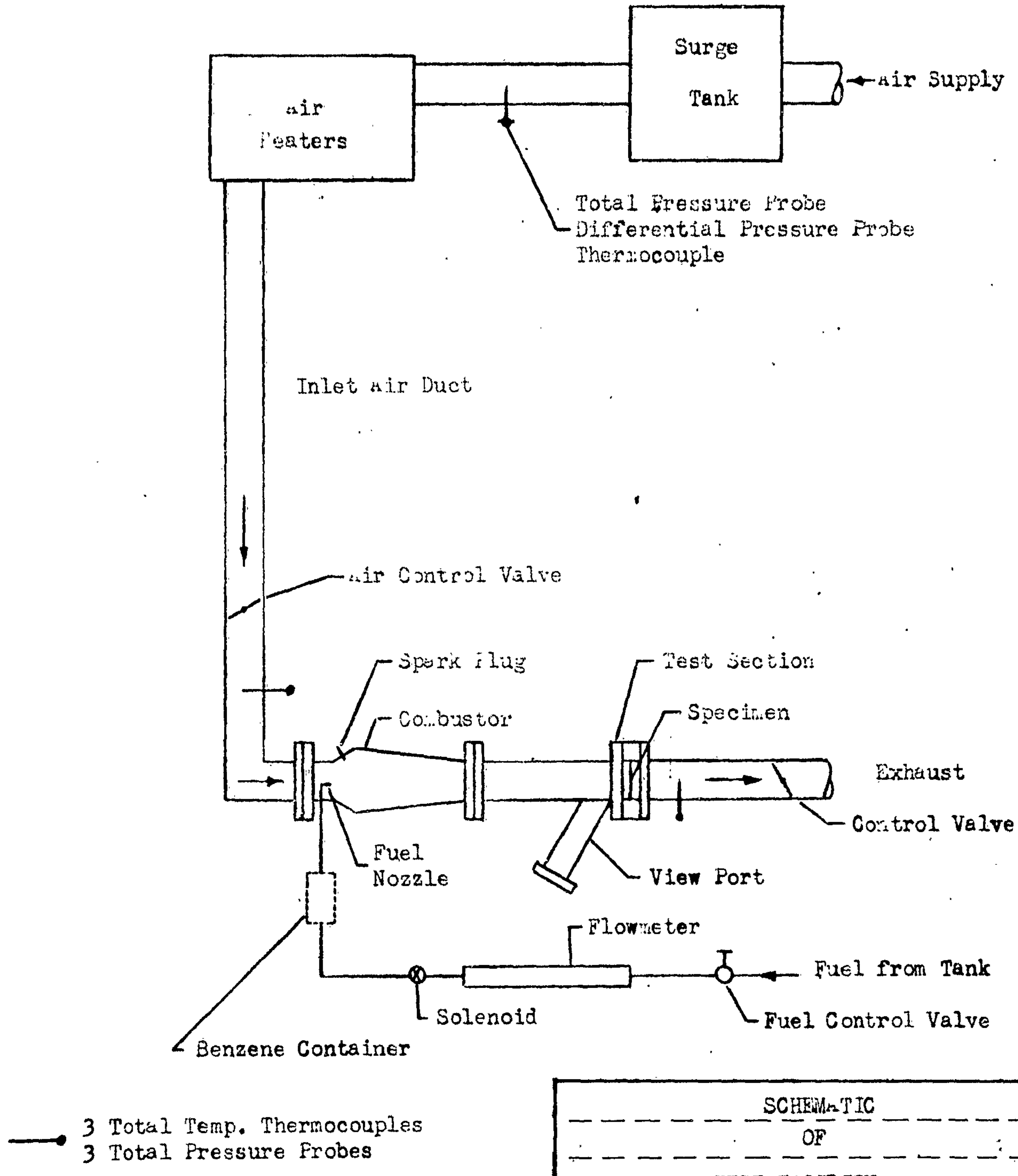
TEST RESULTS

Material	Columbium		Columbium-2% Zirconium	
	Test Temperature - °F/Test Velocity - Ft/Sec			
Fuel	Pass	Fail	Pass	Fail
H_2		1800/60		1800/60
C_3H_8	1800/60		1800/60	
	1800/500		1800/500	
	2000/500			2000/500
		2200/760		2200/760
JP-4		1875/1330*	1610/1330	
		2310/1400	2050/1400	
	2000/1400		1625/1400	
		1625/1400*	2000/1400	
	1825/2400			2110/2400
	2110/2400		1825/2400	

* Failure Questionable - Coating on rod appeared to have ruptured and "healed".

l. An effect of velocity was observed only at the highest temperature and highest velocity test conditions. This effect was an observed permanent deflection of the specimens, which is a function of the elastic limit of the columbium materials and their cross-sectional area.

m. Currently peak turbine inlet temperatures of air breathing gas turbine engines are in the range of 2000 to 2200°F. Since the limiting temperature of the materials tested is in the same temperature range, there would be no advantage gained by the use of these materials in air breathing gas turbine engines using hydrocarbon fuels.



SCHEMATIC

OF

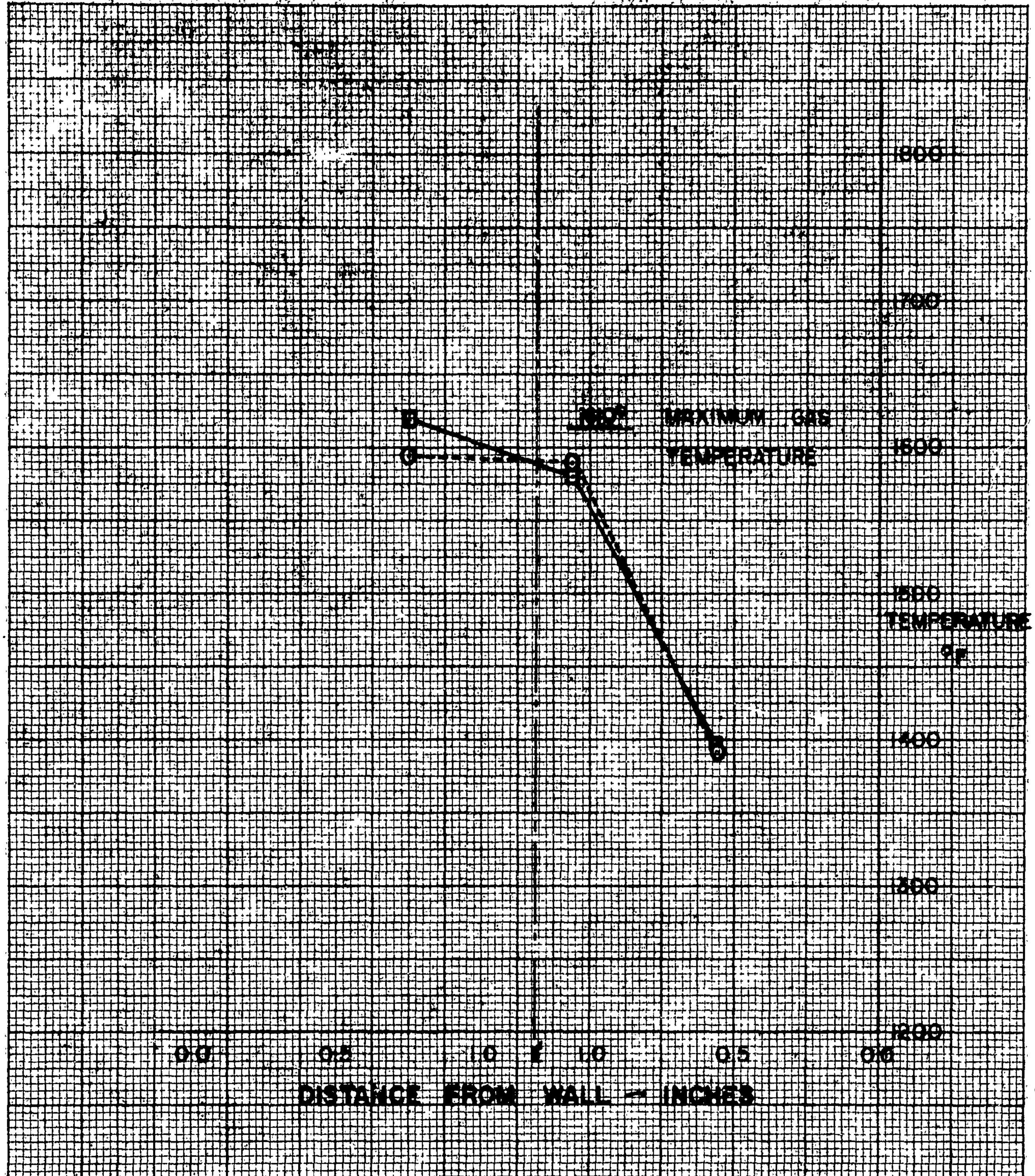
TEST FACILITY

AERONAUTICAL ENGINE LABORATORY

NAVAL AIR MATERIAL CENTER, PHILADELPHIA, PA.

Proj. TED No. NAM PP33001 Engr. S. Fiorello

PLATE 1



POSITION IN TEST SECTION

- ⊙ TOP ROD - MILD STEEL
- ⊡ BOTTOM ROD - STAINLESS STEEL

THERMOCOUPLES WELDED ON SURFACE OF BOTH RODS

RELATIONSHIP BETWEEN EXHAUST GAS AND SPECIMEN SURFACE TEMPERATURE WITH HYDROGEN FUEL

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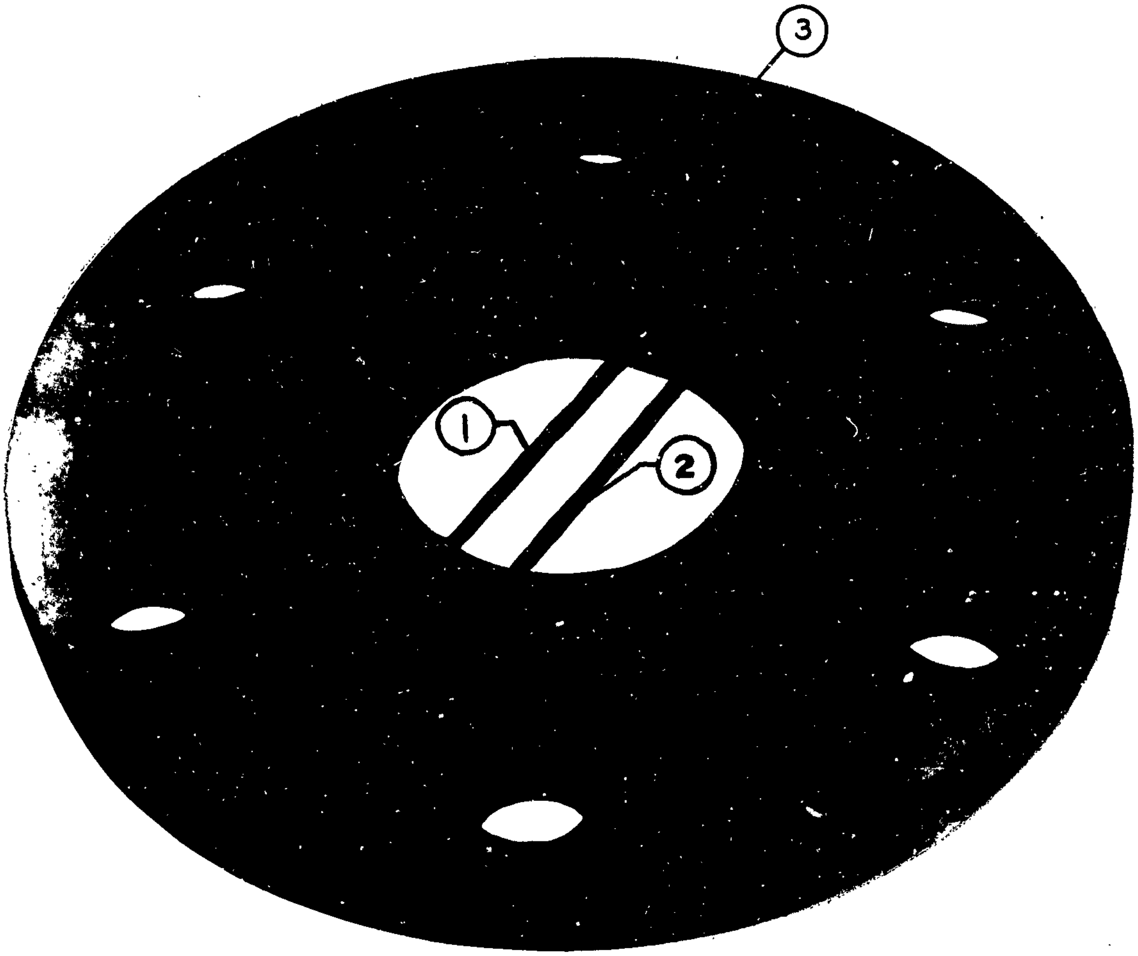
P. A. NAM 33001 ENG'R. S. FIORELLO

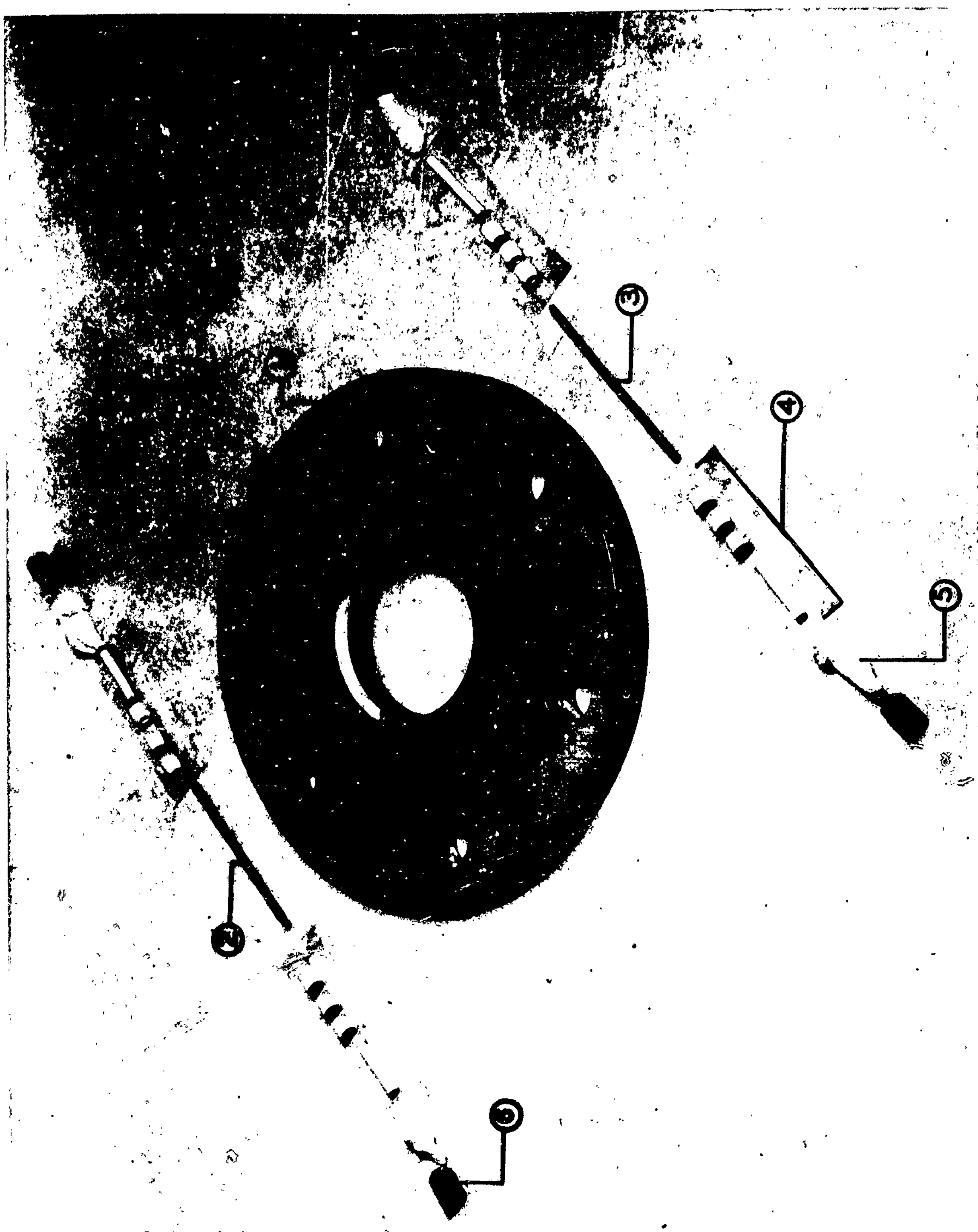


TEST SECTION ASSEMBLED

1 - Pure Cb Rod
2 - Cb plus 2% Zr Rod
3 - Test Section (Stainless Steel)

PHOTO NO: CAN-333625(L)-1-61

PLATE 3

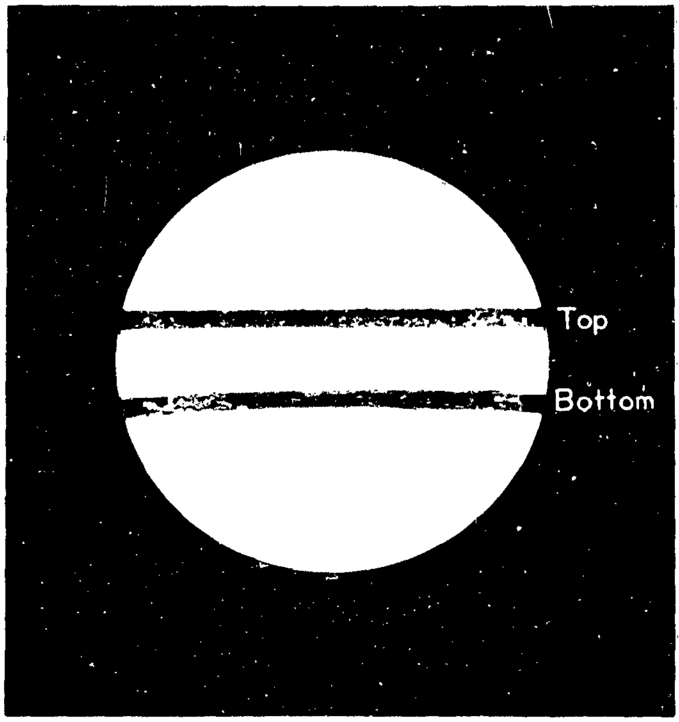


TEST SECTION DISASSEMBLED

1 - Test Section (Stainless Steel)
2 - Pure Cb Rod
3 - Cb plus 2% Zr Rod
4 - Porcelain Supports
5 - Asbestos (String)
6 - Setscrew

PHOTO NO: CAN-333626(L)-1-61

PLATE 4

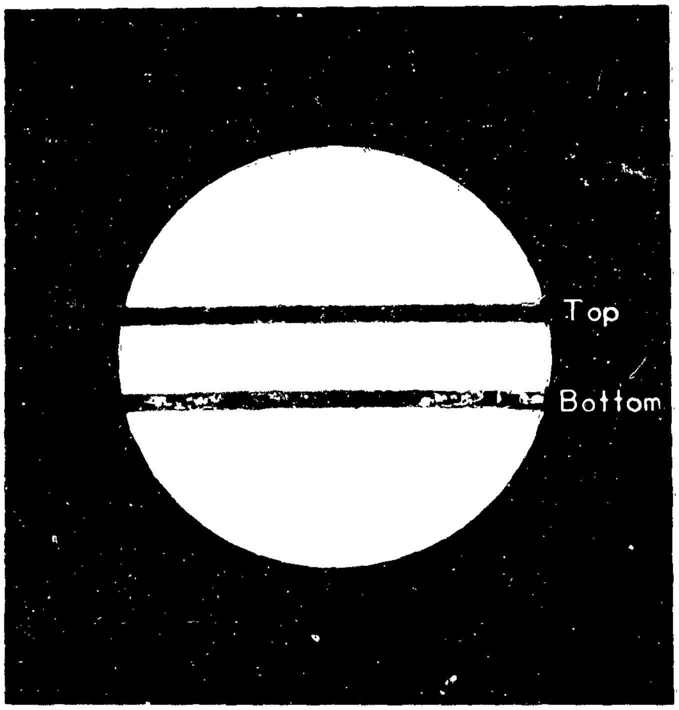


RODS AFTER TEST NO. 8 UPSTREAM

Top Rod --- Zinc Coated Columbium
Bottom Rod -- Zinc Coated Columbium
Plus 2% Zirconium

PHOTO NO: CAN-324714(L)-11-59

PLATE 5

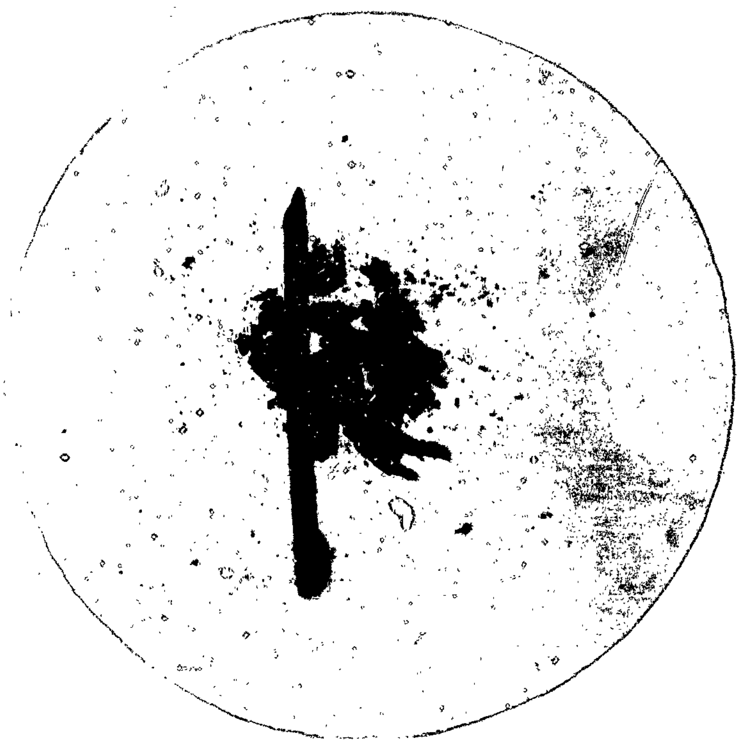


RODS AFTER TEST NO. 8 DOWNSTREAM

Top Rod ---- Zinc Coated Columbium
Bottom Rod --- Zinc Coated Columbium
Plus 2% Zirconium

PHOTO NO: CAN-324713(L)-11-59

PLATE 6



ZINC COATED COLUMBIUM PLUS 2% ZIRCONIUM
WITH CARBON DEPOSIT AFTER TEST NO. 5

PHOTO NO: CAN-324429(L)-11-59

PLATE 7

ZINC COATED COLUMBIUM PLUS 2% ZIRCONIUM
WITHOUT CARBON DEPOSIT AFTER TEST NO. 5

PHOTO NO: CAN-324431(L)-11-59 PLATE 8

UPSTREAM DOWNSTREAM

TEMPERATURE 1800°F

TEMPERATURE 2000°F

TEMPERATURE 2200°F

ZINC COATED COLUMBIUM AFTER EXPOSURE TO PROPANE-AIR COMBUSTION PRODUCTS

PHOTO NO: CAN-333632(L)-1-61

PLATE 9

UPSTREAM DOWNSTREAM

TEMPERATURE 1800°F

TEMPERATURE 2000°F

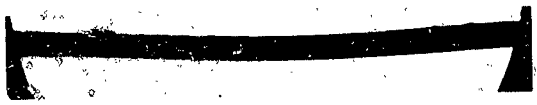
TEMPERATURE 2200°F

ZINC COATED COLUMBIUM+2% ZIRCONIUM AFTER EXPOSURE TO PROPANE-AIR COMBUSTION PRODUCTS

PHOTO NO: CAN-333633(L)-1-61

PLATE 10

UPSTREAM DOWNSTREAM



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TEMPERATURE 1625°F

TEMPERATURE 1825°F

TEMPERATURE 1875°F

ZINC COATED COLUMBIUM AFTER EXPOSURE TO JP-4-AIR COMBUSTION PRODUCTS
(1625°F -- 1875°F)

PHOTO NO:CAN-333634(L)-1-61

PLATE 11

UPSTREAM DOWNSTREAM

TEMPERATURE 2000°F

TEMPERATURE 2110°F

TEMPERATURE 2310°F

ZRO COATED COLUMBIUM AFTER EXPOSURE TO JP-4-AIR
COMBUSTION PRODUCTS
(2000°F -- 2310°F)

PHOTO NO: CAN-333635

PLATE 12

UPSTREAM DOWNSTREAM

TEMPERATURE 1610°F

TEMPEPATURE 1625°F

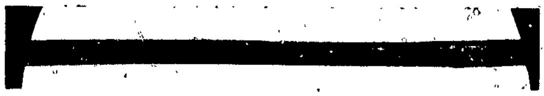
TEMPERATURE 1825°F

ZINC COATED COLUMBIUM + 2% ZIRCONIUM AFTER EXPOSURE
TO JP-4-AIR COMBUSTION PRODUCTS
(1610°F - 1825°F)

PHOTO NO: CAN-333636(L)-1-61

PLATE 13

UPSTREAM DOWNSTREAM



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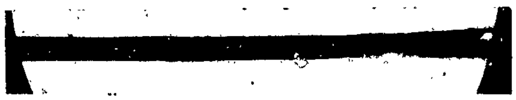
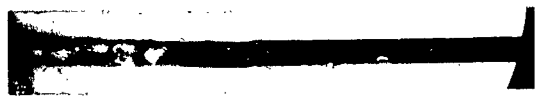
TEMPERATURE 2000°F





TEMPERATURE 2050°F

TEMPERATURE 2110°F

ZINC COATED COLUMBIUM + 2% ZIRCONIUM AFTER EXPOSURE TO JP-4-AIR COMBUSTION PRODUCTS (2000°F - 2110°F)

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